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Production of a Single Heavy Quark in e^+e^- Collisions

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ABSTRACT

Cross sections for the flavor changing neutral transition $e^+e^- \to \bar{t}c$ are calculated in the standard model with three generations, and found to be unmeasurable; $e^+e^- \to \bar{b}s$ is a few orders of magnitude larger. Experimentalists should nevertheless look for these processes since an increase in the number of generations, strong interaction effects and mainly non-standard models may lead to observable rates. Z^0 decays into a single heavy quark plus a light one are also briefly discussed.

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Observation of a $t\bar{t}$ state in e^+e^- collisions requires center of mass energies $E_{cm} > 2m_t$. Suppose that the maximum energy available in e^+e^- machines is only $E_{cm} \simeq m_t$. Is it still possible to observe the top quark using such an accelerator? The answer to this question depends on the magnitude of the rates for flavor changing processes such as $e^+e^- \to \bar{t}c$ at high energies. Until recently effects of loops in the standard $SU(2) \times U(1)$ model at high energies have been calculated in the lepton sector only,[1] with resulting small rates. The flavor changing vertex $ij\gamma$, where i,j denote quark flavors and the photon is highly virtual, was first calculated in the standard model for any internal and external quark masses in Ref. (2). We use here that calculation to find the cross sections for $e^+e^- \to \bar{Q}q$ where Q,q are heavy and light quarks, respectively.

In the standard model with 3 generations we find very small results for $e^+e^- \to \bar{t}c$, where the Glashow-Iliopoulos-Maiani (GIM) mechanism[3] is an effective suppressor. By adding another generation the rates are increased; furthermore, strong interaction effects of the penguin type (which are not calculated here) may increase the rate, but will probably still leave it out of experimental reach. Non-standard models, on which we only comment here, can lead to measurable rates for $e^+e^- \to t\bar{c}$.

The GIM mechanism can be overcome in $e^+e^- \to \bar{b}s$ where the top quark runs in the loop. In that case, and for high m_t with strong interaction corrections the rates may in principle be measurable, though of course the signature is not as definite as in $e^+e^- \to \bar{t}c$. $Z^0 \to \bar{Q}q$ is another place to look for top quarks[4] if $m_t > M_Z/2$.

The cross section for the process $e^+e^- \to \bar{Q}q$, shown in Fig.1 for Q = t, q = c, is given by

$$\sigma(e^+e^- \to \bar{Q}q) = \frac{3}{128\pi s} \sum_{\text{spins}} \int_{-1}^{1} dx\,|T(x)|^2 \tag{1}$$

where $x = \cos\theta$ (θ is the angle between c and e^-) and s is the c.m. energy squared. The factor 3 is from color, and at the end of the calculation the result is multiplied by an extra factor of 2, since $\sigma(e^+e^- \to Q\bar{q})+\sigma(e^+e^- \to \bar{Q}q)$ will be considered. The matrix element for photon exchange is given in obvious notation by

$$T = \frac{-ie}{s}\, \bar{u}_c \Gamma^\mu_{Ren} v_t \bar{v}_{e^+} \gamma_\mu u_{e^-} \ . \tag{2}$$

The renormalized flavor changing electromagnetic vertex Γ^μ_{Ren} includes the couplings and is shown in Figs. 2 and 3. It can be written as

$$\Gamma^\mu_{Ren} = (A_L p^\mu + B_L k^\mu + C_L \gamma^\mu) L + (A_R p^\mu + B_R k^\mu + C_R \gamma^\mu) R \tag{3}$$

with $L,R=(1\mp\gamma_5)/2$ and $p=-p_t$, $k=-(p_c+p_t)$. As can be seen by comparing Eq. (3) with Eq. (E3) of Ref. (2), the coefficients A_L, B_L, C_L, A_R, B_R, C_R are given there as linear combinations of A_i and B_i $(1\leq i\leq 13)$. A_i and B_i were computed in Ref. (2), and are given in the table there; their on-shell values should be inserted in the expression for Γ^{μ}_{Ren}. The trace in Eq. (1) is then straightforward but lengthy, and will not be shown here.[6] The sum over d,s,b quarks in the loop is performed with the following central values of the Kobayashi-Maskawa (KM) angles:[7] $s_1=0.228$, $s_2=0.1$, $s_3=0.3$, $s_\delta=0.03(\delta\simeq 0)$, and with masses: $m_d=0.0075$ GeV, $m_s=0.15$ GeV, $m_b=4.7$ GeV, $m_c=1.2$ GeV.

Typical results for $R=\sigma(e^+e^- \to t\bar{c})/\sigma(e^+e^- \to \mu^+\mu^-)$ are shown in Table 1; the rates are clearly too small to be observable. Also shown in Table 1 are values of R when a fourth generation b' quark is added, setting arbitrarily $m_{b'}=400$ GeV and $s_4=0.3$ in a 4×4 generalization of the KM matrix. The rates are unobservable, even though the signature of two unequal jets is very distinct. The smallness of the rates is of course the result of both the high order nature of the process and the very effective GIM suppression. The GIM mechanism is extremely painful here since $s \gg m_q^2$ for all quarks q in the loop.

Strong interactions can also increase these very small rates. I have in mind the following effect: In the standard SU(2) × U(1) model the dipole moment of the neutron is very small,[8] $D_n/e \simeq 10^{-34}$cm. It was pointed out[9] that strong interactions of the penguin type can increase D_n by 2–3 orders of magnitude, since the GIM cancellation will be only logarithmic. A similar effect may operate for $e^+e^- \to Q\bar{q}$, but a detailed calculation of two loops diagrams (a gluon and a W run in each loop) is needed, since the considerations for D_n involve $k^2=0$, while k^2 is large here. It does not seem though that the rates for $e^+e^- \to t\bar{c}$ will turn out to be measurable in the standard model.

If the possibility to observe directly a top quark with $m_t \simeq E_{cm}$ has to be abandoned, one still has the option to consider t quarks in loops.[10] To this end I now discuss $e^+e^- \to b\bar{s}$. The GIM cancellation is not so severe here since m_t is much larger than the other quark masses in the loop, and it is never much smaller than $\sqrt{s}$. Values for $R=\sigma(e^+e^- \to b\bar{s}+\bar{b}s)/\sigma(e^+e^- \to \mu^+\mu^-)$ are shown in Tables 2 and 3 for $\sqrt{s}$=38, 260 GeV, respectively as a function of m_t/M_W,[11] with 3 generations. A fourth generation will not make such a difference here, since GIM cancellation has already been overcome by m_t, but strong interaction effects of the penguin type may increase the rates substantially. Without these effects about an event per year is expected at the highest energy projected in LEP. The signature for $e^+e^- \to b\bar{s}$ is of course not as distinct as for $e^+e^- \to t\bar{c}$, but the special characteristic of a b jet can be used to distinguish it from other jets (as being currently done in order to investigate $e^+e^- \to b\bar{b}$). On the level presented in Tables 2 and 3 this is not feasible, so we should hope that strong interactions will change the picture.

In LEP, one expects 10^8 Z^0 decays per year, and if $m_t > M_Z/2$ then $Z^0 \to t\bar{c}$ should be considered as a method to observe the top quark. Unfortunately the rates are unobservable.[4] For $Z^0 \to b\bar{s}$ however, branching ratios of approximately 10^{-6} are expected for high m_t, thus making it possible to observe a decay rate which is sensitive to the top quark in the loop. Again, strong interactions have to be considered and a fourth generation down quark can lead to an observable rate even for $Z^0 \to t\bar{c}$.

Other possibilities to observe effects of a heavy top quark in e^+e^- collisions are $e^+e^- \to b\bar{b}$, or $Z^0 \to b\bar{b}$ where there is no GIM mechanism, and the angular distributions will be affected by the induced couplings arising from the loop contributions. I have not yet done a quantitative calculation of this effect.

It seems that all the rates discussed above are either unmeasurable or very difficult to observe in the framework of the standard $SU(2) \times U(1)$ model. The situation here is similar to the case of the electric dipole moment of the neutron, where only non-standard generalizations, such as the introduction of charged Higgs particles[12] or left-right symmetric models,[13] can give an observable D_n. Experimentalists should therefore search for $e^+e^- \to t\bar{c}$ since any observable effect is an indication of something very interesting. Flavor changing neutral Higgs particles[14] and weak interaction models without universality among generations[15] are two obvious candidates that can lead to a measurable rate.

To summarize, the rates for flavor changing electromagnetic transitions in e^+e^- collisions were calculated in the SU(2) × U(1) standard model. Production of a single top is unobservable, and production of a single b quark is possible only if strong interaction effects, which have not been calculated yet, enhance the rate by at least two orders of magnitude. Z^0 decays, and effects of a heavy quark on flavor conserving transitions were also briefly discussed. The results presented here should encourage, rather than discourage experimentalists to look for the distinct signals of $e^+e^- \rightarrow t\bar{c}$ and $Z^0 \rightarrow t\bar{c}$ since very interesting physics can show up.

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TABLE CAPTIONS

Table 1: The ratio $R=\sigma(e^+e^- \to t\bar{c}+\bar{t}c)/\sigma(e^+e^- \to \mu^+\mu^-)$ in the standard model for two sets of $\sqrt{s}, m_t$ values with 3 and 4 generations (for the latter case $m_b' = 400$ GeV). In all the tables strong interaction effects are not included.

Table 2: The ratio $R=\sigma(e^+e^- \to b\bar{s}+\bar{b}s)/\sigma(e^+e^- \to \mu^+\mu^-)$ at $\sqrt{s} = 38$ GeV in the standard model.

Table 3: The same ratio as in Table 1, at $\sqrt{s} = 260$ GeV.

FIGURE CAPTIONS

Fig. 1: The flavor changing process $e^+e^- \to \bar{t}c$ in the standard model.

Fig. 2: The renormalized electromagnetic flavor changing vertex equals the unrenormalized past Γ^μ plus a counterterm.

Fig. 3: The flavor changing vertex, where i, j and l denote flavors, and its decomposition in the 't Hooft-Feynman gauge with on-shell renormalization. ϕ stands for the unphysical scalar which always accompanies the W boson.

TABLE 1

		$\sqrt{s}$, m_t (GeV)	38, 30	260, 150
R	3 generations	$4.6\cdot10^{-12}$	$4.7\cdot10^{-9}$
	4 generations	$1.9\cdot10^{-10}$	$6.2\cdot10^{-7}$

TABLE 2

$\frac{m_t}{M_W}$	0.25	0.5	1	1.5	2	2.5	3	3.5	4
R	$6.0\cdot10^{-8}$	$8.1\cdot10^{-8}$	$1.2\cdot10^{-7}$	$1.5\cdot10^{-7}$	$1.7\cdot10^{-7}$	$1.9\cdot10^{-7}$	$2.0\cdot10^{-7}$	$2.2\cdot10^{-7}$	$2.3\cdot10^{-7}$

TABLE 3

$\frac{m_t}{M_W}$	1.6	2	2.5	3	3.5	4
R	$1.1\cdot10^{-4}$	$1.6\cdot10^{-4}$	$2.0\cdot10^{-4}$	$2.3\cdot10^{-4}$	$2.5\cdot10^{-4}$	$2.6\cdot10^{-4}$

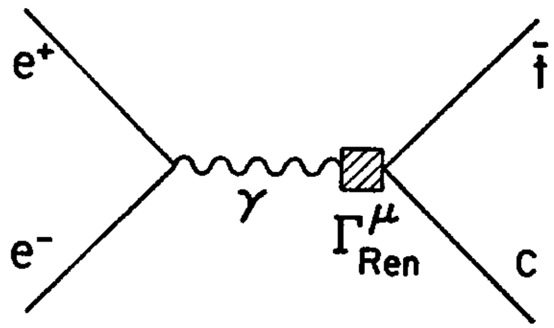

Fig. 1

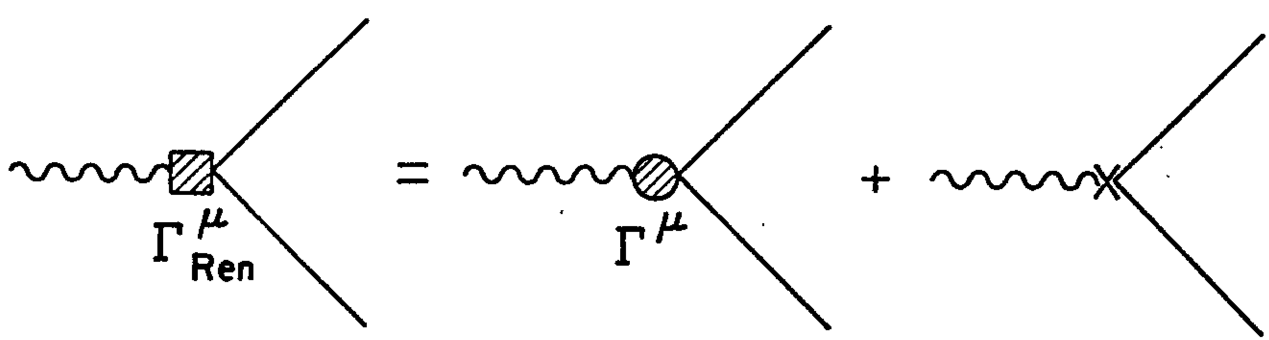

Fig. 2

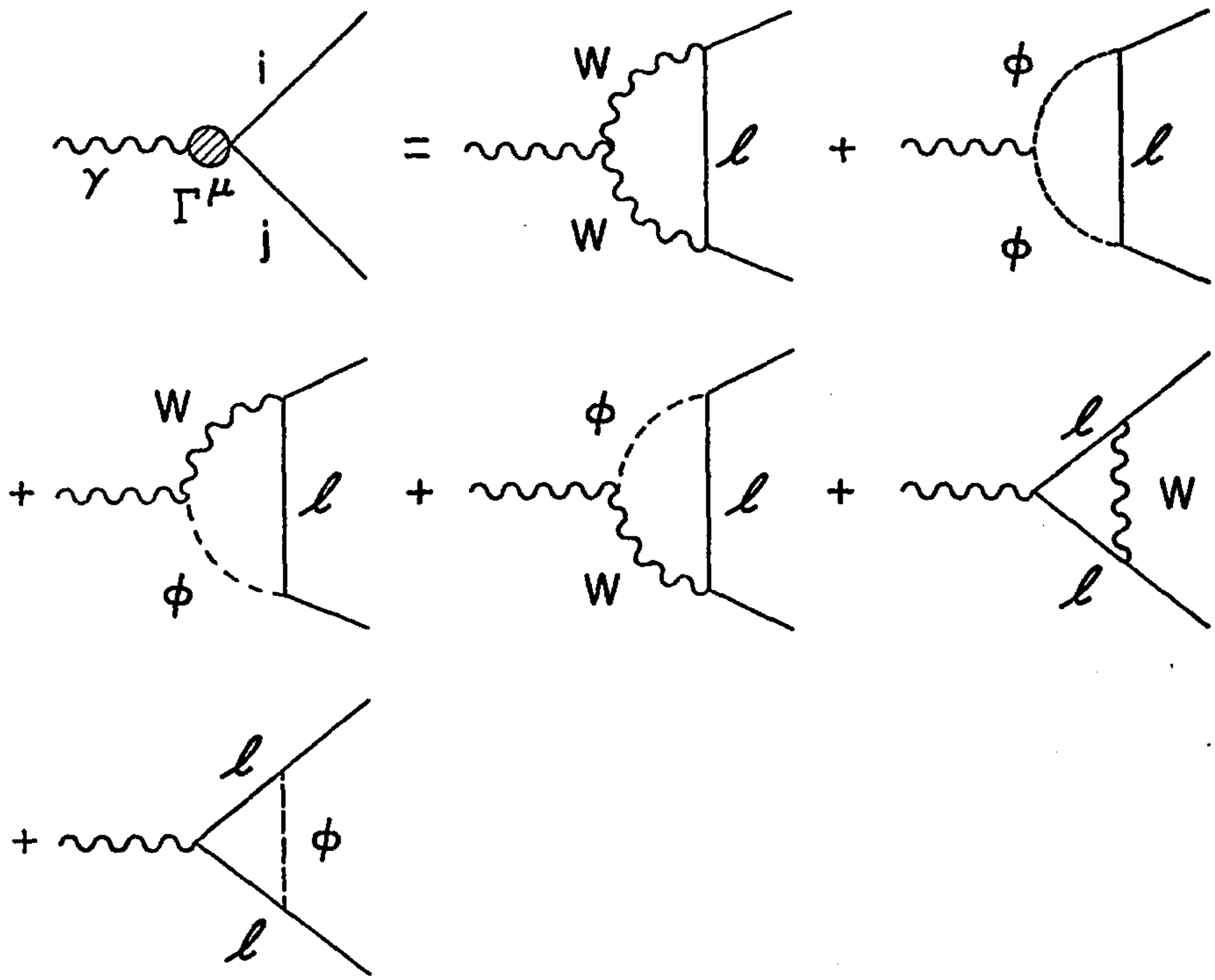

Fig. 3